A Driving Force

Paul B. MacCready has a knack for knowing the difference between the impossible and that which is merely extremely difficult. In the late 1980s, MacCready, founder and CEO of AeroVironment, a company that consults on pollution management and wind energy, figured that a battery-powered automobile could be practical, provided the entire machine was optimized for efficiency. It would have to be exceptionally lightweight and streamlined to a degree never before seen in commercial cars. MacCready's idea became General Motors' EV1, now marketed in southern California and Arizona by Saturn dealers.

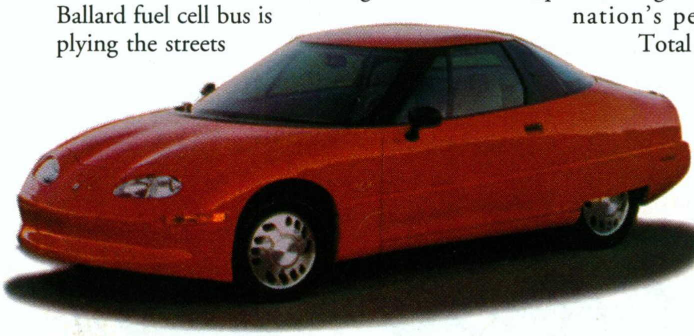
Meanwhile, fuel cells, which supplied electricity on the Gemini space capsules of the mid-1960s, are widely considered to be the ultimate in efficiency and cleanliness. Unfortunately, as far as cars were concerned, they were considered pie in the sky. But unexpectedly fast developments this decade have brought fuel cells down to earth, and now Daimler-Benz, the maker of Mercedes, and Ballard Power Systems of Vancouver, Canada, have announced a $350 million-plus joint venture to market fuel cells as automobile engines. One Ballard fuel cell bus is plying the streets of Vancouver and six more will be ferrying Chicagoans and British Columbians later this year. Ford and Chrysler have also recently announced ambitious fuel cell programs.

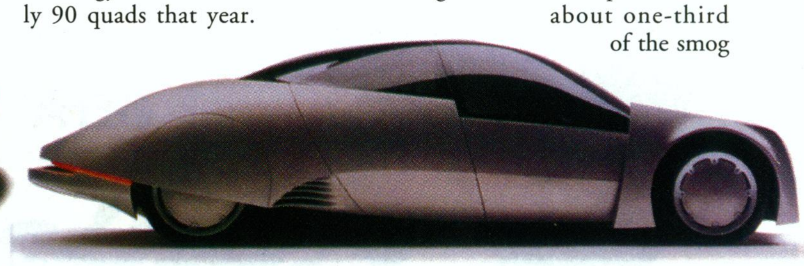
Other technologies vying to power cars of the future range from cleaner gasoline and diesel engines, to miniature gas turbines, to internal combustion/electric hybrids, to incredibly efficient Stirling-technology external combustion engines. In addition, an estimated 385,744 alternative fueled vehicles are currently in use in the United States, according to *Alternatives to Traditional Transportation Fuels 1995*, a December 1996 publication of the Energy Information Administration. These include 273,000 vehicles that run on liquid petroleum gases, 81,000 that run on compressed natural gas, 26,000 that run on 85% alcohol, and 3,900 electric vehicles (EVs).

The Need for Alternative Vehicles and Fuels

In 1996, the United States' automobiles, minivans, and sport utility vehicles burned 15 quadrillion British thermal units (quads) of gasoline, two-thirds of the nation's petroleum consumption. Total U.S. energy use was nearly 90 quads that year. Half of the United States' petroleum comes from abroad, and the cost of importing oil is $100,000 every minute, says Jason Mark, a transportation analyst with the Union of Concerned Scientists' Berkeley, California, office. Although the rest of the economy became more energy-efficient after the 1979 oil shock, says Mark, consumers have little incentive to demand more energy-efficient autos, as fuel accounts for only 15% of the cost of car ownership. Still, costs are not the only reason to develop alternatives to gasoline-powered vehicles.

Another reason is air pollution. Ozone, a powerful respiratory irritant found in most of the nation's urban areas during summer months, is estimated to kill several thousand Americans annually through its contribution to lung disease, says Ronald H. White, deputy director of national programs for the American Lung Association in Washington, DC. According to the EPA, ozone is linked to approximately 10,000–15,000 hospital admissions and 30,000–50,000 emergency room visits annually in 13 metropolitan areas. Ozone forms when hydrocarbons and nitrogen oxides (NOx), two important constituents of automobile exhaust, react in the presence of sunlight. Cars are responsible for about one-third of the smog





in the Los Angeles Basin, says Carl Moyer, chief scientist at Acurex Environmental Corporation in Mountain View, California.

Changes in vehicles and fuels could also mitigate some of the problems associated with global warming, which is caused by emissions of carbon dioxide (CO_2) and other greenhouse gases. Cars account for nearly 20% of CO_2 emissions in the United States and 15% of emissions worldwide, says James Ohi, team leader for light duty vehicle research and development at the National Renewable Energy Laboratory in Golden, Colorado. The United States contributes a total of 23% of the world's burden of CO_2, and CO_2 accounts for about 60–70% of greenhouse gas emissions.

The Clean Air Act of 1994 set current tailpipe standards for hydrocarbons, carbon monoxide (CO), and NOx at 0.25, 3.4, and 0.4 grams per mile, respectively. Due to the extreme prevalence of smog in Los Angeles, the EPA allows California to set its own standards. Other states may opt to follow California's standards, but only Massachusetts and New York have done so.

The California Air Resources Board (CARB) had planned to require that 2% of all cars sold in California in 1998 produce zero emissions—which is tantamount to mandating battery power—increasing to 10% of all car sales in 2003. But the state backed down last December because it became clear that the demand for range-limited vehicles would be too low to meet the mandate, and because a backlash against EVs was feared.

Instead, car makers are now required to put 3,750 electric cars on the road between 1998 and 2000, says Mark, and are offered incentives to do so early. For example, cars with more advanced batteries than lead acid are double-counted (nickel metal hydride) or triple-counted (lithium ion). The requirement of 10% zero-emissions vehicles (ZEVs) by 2003 remains in place, although the earlier standards do not.

Another regulatory motivator is the Energy Policy Act of 1992. The goal of this act is to replace 10% of gasoline usage with alternative fuels (including reformulated gasoline in addition to fuels such as methanol and natural gas) by the year 2000. Ten percent of vehicles purchased by federal and state agencies in 1997 must be powered by alternative fuels, rising to 50% in model year 2000, and 75% thereafter.

The act also provides some incentives: a $2,000 grant per vehicle for alternative fuel vehicles, a tax credit of 10% of purchase price capped at $4,000 for EVs, and a tax deduction of up to $2,000 for investment in alternative fuel refueling stations, says Paul McArdle, an economist with the Department of Energy (DOE).

PNGV

In an elaborate ceremony in the White House Rose Garden on 29 September 1993, President Clinton inaugurated the Partnership for a New Generation of Vehicles (PNGV). The "Big Three" U.S. auto makers (Ford, General Motors, and Chrysler) agreed that 10 years hence, each would have produced prototypes of low-emissions cars "that would get 80 miles per gallon, and be affordable on the same basis as the Ford Taurus, the Chevrolet Lumina, and the Chrysler Concorde," says Robert M. Chapman, former chairman of the PNGV Task Force, who is now a consultant with the California-based RAND Corporation. These prototypes would also equal current vehicles in performance, amenities, and convenience, although the Rocky Mountain Institute (RMI), a think tank in Old Snowmass, Colorado, characterizes PNGV acceleration goals (0–60 miles per hour in 12 seconds) as "doggish."

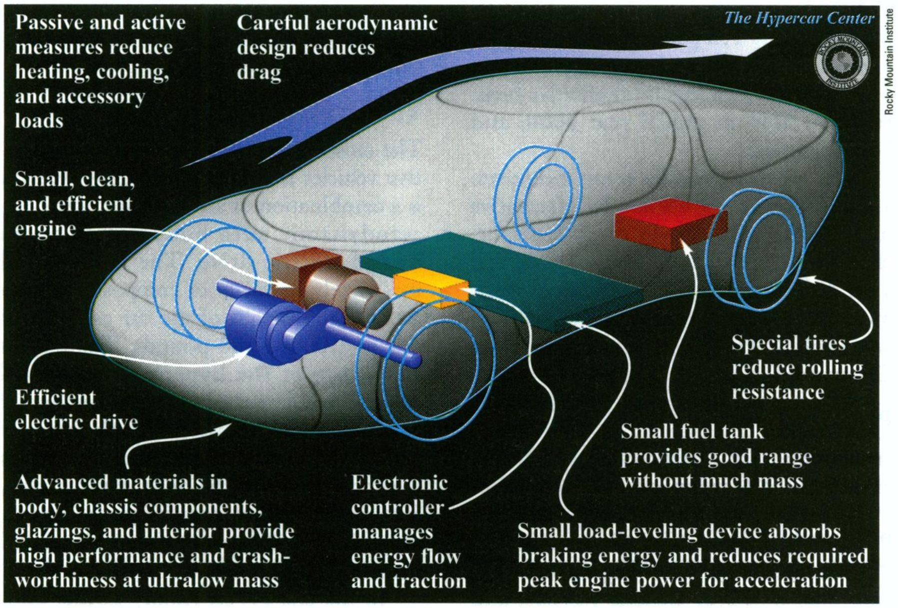
The federal government spends roughly $300 million annually on the PNGV, says Chapman, money that was previously spent on automotive research and development but that is now being put towards the PNGV's goals. The auto makers match this sum. This may sound like a lot of money, but insiders believe that Toyota alone is spending more to develop alternatives than all U.S. companies combined. Officially, Toyota is mum on the numbers, but last year, Japanese newspapers reported that the company planned to spend more than $800 million annually, says Daniel Hoff, electric vehicle administrator at Toyota Motor Sales, USA in Torrance, California.

The Hypercar

The most ambitious design idea in alternative vehicles is the hypercar. The hypercar is a combination of an ultralight, low-drag, aerodynamic auto body design and a hybrid electric drive. The body would most likely be made of composite materials, and the weight of the car could be as low as 1,000–1,500 pounds. The biggest advantage of the hypercar is that fuel mileage could be the gasoline equivalent of as much as 300 mpg. Although hypercar designs have been elaborated in detail, a hypercar has yet to be built. Furthermore, a hypercar would require considerably more design effort than a conventional automobile.

In the late 1970s, Amory Lovins (now vice president, chief financial officer, director of research, and cofounder of RMI) earned the wrath of the utility industry by claiming that investments in efficient energy were far sounder than investments in nuclear plants. Soon, the same companies were hiring Lovins as a consultant. The 1993 MacArthur "genius award" winner has advised over 100 utilities worldwide on how to profit from what he calls the "negawatt" (energy conservation) industry, which grosses about $5 billion annually in the United States alone. Now, like the utility executives of yore, car company executives are reluctantly accepting that they must listen to this voice of change in order to satisfy both the government and the market. Lovins is not asking people to do without in order to save the planet; his method for changing the world is to provide something people will want. The first company that markets what RMI calls the hypercar will have consumers flocking to its showrooms, because it will provide superior

Hitting the ground running. (left to right) Chrysler, Ford, General Motors, and Toyota are all introducing electric or hybrid vehicles as part of their automotive offerings to an environmentally conscientious public. Photo credit: USCAR



If it just had wings. Hypercars are designed for maximum fuel efficiency and minimum friction.

acceleration, handling, braking, safety, and durability in a package that is just as roomy and comfortable as today's Chevrolet, Lovins predicts. Major auto companies are heeding Lovins's prediction and knocking on his door at RMI for advice.

The guiding concept behind hypercar design flows from the design principle that major reductions in body mass allow still greater reductions in mass—smaller motors, smaller brakes, etc.—to the point where ancillary systems such as power steering and power brake boosters become superfluous. Hybrid electric drive systems can displace other components too, such as the starter, alternator, axles, differentials, multispeed transmission, clutch, driveshaft, and universal joints, according to an RMI paper, *Speeding the Transition: Designing a Fuel-Cell Hypercar*.

The first step in hypercar design is to replace steel bodies with ultralight advanced composite materials. The body, the most massive system, currently represents almost one-fourth of a vehicle's curb weight, according to RMI. Use of advanced polymers like carbon fiber reinforcement could reduce a car's mass by 50–67%, compared with a 40–50% reduction for aluminum bodies. A similar shift has already transformed boat-building and aeronautics. Use of advanced composites also simplifies manufacturing. Composites can be formed far more easily than steel and into more complex structures, so a multitude of panels can be replaced by a single structure.

The hypercar would increase fuel mileage to 90–150 mpg, according to RMI, which claims 200-mpg cars are possible. Reduction in CO_2 emissions would be proportional to, or better than, fuel economy improvement, depending on the type of fuel used and optimization strategy.

RMI's calculations are controversial among auto companies partly because a hypercar has never been built. Additionally, the concept would force manufacturers to change the way they build cars, something they seem bound to resist. "We question the mathematics [RMI] uses," says Walter Kreucher, manager of advanced environmental and fuels engineering at Ford Motor Company in Dearborn, Michigan, "[because] we've never seen a car built that gets what [they] think is theoretically possible." Kreucher continued to say that "[RMI] compounds certain assumptions already built into most automobiles today," but he refused to be more specific than that.

"We had a team out there just a few months ago," says Ronald York, PNGV program director at General Motors in Warren, Michigan. "The concepts we agree on . . . but [RMI] doesn't fully appreciate the complexities of things that work against you." He cites the heat rejection requirements of fuel cells and Stirling engines (two drive units that could be important in hypercars as well as in more conventional advanced vehicles), which would require "a massive radiator," and increase aerodynamic drag. But Timothy Moore, chief designer at the RMI Hypercar Center, claims these weaknesses are negligible. Besides, he says, there are other options for motive systems in hypercars besides fuel cells and Stirling engines, and "this is just another one of many trade-offs in a long list, as to what kind of power plant to put in a car."

Nonetheless, Ford's prototype PNGV car, the P2000, is impressive. RMI's Brett Williams, research associate for hydrogen and fuel cells, and Moore have modeled a fuel-cell powered hypercar based on PNGV criteria. "We think you can do even better with advanced composites, but [Ford's] numbers are good enough," he says. The P2000; designed to provide the space and comfort of a Ford Taurus, will be over 1,200 pounds lighter than the Taurus, according to Ford. Body weight—including all body-related components—will drop from 1,571 to 875 pounds, the chassis (components, not structure) from 813 to 478 pounds, the powertrain from 794 to 569 pounds, and fuel from 140 to 78 pounds. Several different drives will be tested in the P2000—two of them electric hybrids—and the first prototypes will be assembled this fall.

Battery Power

While some researchers pare mass from cars, others are developing new drive systems. Most of the major manufacturers are experimenting with battery power. General Motors' EV1 will get nickel metal hydride batteries later this year, which the company claims will double the car's range. Toyota's RAV4, a nickel metal hydride battery-powered version of its sport utility vehicle, provides a range of 130 miles and can be 80% recharged in three hours, according to company spokesman Jeremy Barnes. About 10 of the vehicles are leased to utility companies in California and New York. Nissan's Prairie Joy, a compact minivan, can go 120 miles between charges on 750 pounds of lithium ion batteries (the kind that qualify for triple credit with the CARB), says John Schutz, director of regulatory affairs for Nissan Research and Development in Los Angeles. A handful of Prairie Joys are leased in Japan, and they are scheduled to arrive stateside next year.

But without a breakthrough, battery power won't be driving many commercial EVs. The reason is simple: existing cars have a range of about 380 miles. In the world of EVs, that's extremely expensive to obtain. Even battery advocates concede their limitations. Rick Tempchin, director of electric transportation at the Edison Electric Institute in Washington, DC, a trade association for investor-owned utilities, talks about encouraging EV use by providing incentives such as access to high-occupancy vehicle lanes and better access to parking.

Good luck. A survey released 20 May 1997 by J.D. Powers and Associates, a marketing firm headquartered in Agoura Hills, California, suggests few consumers would buy electric cars without major breakthroughs. "Range between refueling is the single largest disadvantage of the EV, and the single largest advantage of the gasoline-powered vehicle," says Timothy Gohmann, director of custom research at Powers. Ease of refueling was the second biggest advantage of gasoline power and the second biggest weakness of EVs.

Clean, Efficient Combustion

There are several ways to use combustion to power automobiles more cleanly and efficiently than is done today. Conventional technologies, such as today's internal combustion engines and compression-ignition direct-injection (CIDI) engines, are being made to run more cleanly and efficiently. On the other hand, external combustion Stirling engines have far fewer moving parts than internal combustion engines, and are potentially cleaner and far more efficient as well.

Internal combustion could conceivably remain important for years to come. Internal combustion engines have become steadily cleaner, and in January 1995, American Honda Motor Company, Inc., based in Torrance, California, announced that it had become the first manufacturer to develop a production-based gasoline engine that had been certified by the CARB as meeting the Ultra Low Emission Vehicle (ULEV) exhaust standards.

The 4-cylinder engine will be available in Hondas beginning with the 1998 model year. It features improvements on Honda's patented VTEC engine, including a fast warm-up catalytic converter. (Most combustion engine emissions occur during the first few minutes, before the catalytic converter has warmed up.) Horsepower, torque, and gas mileage are expected to be virtually unchanged.

While advanced versions of conventional gasoline engines such as Honda's can be made very clean, CIDIs, the subject of much research of late, are considerably more efficient than conventional gasoline engines. A CIDI engine operates under the same principle as a diesel engine, but it does not need to run on diesel fuel. Under optimum conditions, such as steady highway driving, a gasoline engine can convert roughly 25% of the energy of fuel into forward motion, while CIDIs and diesel engines run at a more fuel-efficient level of 35%. However, important questions about emissions of diesel engines remain and, in fact, there is frequently a trade-off between efficiency and emissions.

General Motors is working with the DOE and Stirling Thermal Motors of Ann Arbor, Michigan, to develop the Stirling engine for automobiles. In theory, it can attain a higher efficiency than any other type of heat engine (or mechanical device that converts heat into work). Although the Stirling engine runs on gasoline, emissions are potentially very low, possibly one-tenth of the CARB's ULEV standard in an efficient hybrid drive system, says Moore.

York describes the Stirling engine as the "mechanical embodiment of the Carnot cycle," meaning it runs at peak efficiency. The Stirling was used in ships in the early 19th century before steam engines were adopted, and uses an external heat source to heat a working fluid (ideally hydrogen gas), which pushes four pistons in a pattern that is converted to rotary motion.

One of the biggest difficulties has been to reduce Stirling engines to a size suitable for cars. But General Motors has managed to place a Stirling-powered hybrid electric drive system into a Chevrolet Lumina. Another challenge has to do with the working fluid. "Those little-devil hydrogen molecules have a bad habit of leaking out," says York. "What we think of as solid metal is porous to them."

Combustion/Electric Hybrids

A hybrid is a conveyance that uses two types of power source instead of one (e.g., a heat engine and an electric motor). In a "series" hybrid, a combustion engine (or fuel cell) generates power to run an electric motor that drives the wheels. In a "parallel" hybrid, the combustion engine can also drive the wheels directly. Compared with direct drive by combustion engine, hybrids are considerably more efficient and cleaner. Unlike battery-driven electrics, they have neither acute range limitations nor long refueling times.

Either arrangement offers several advantages. The combustion engine "can run at its 'sweet spot,'" says Williams, which improves efficiency and reduces emissions. Electric drives require simpler or no transmissions. The engine can be far smaller than in a conventional drive without sacrificing acceleration. The electric motors provide high torque even at low speeds. Further efficiency can be gained by using regenerative braking, in which unused energy is channeled back to the battery during braking.

Nonetheless, questions need to be resolved. "Load leveling" (additional power capacity from a small battery) is needed since output from the combustion engine will rarely equal drive motor requirements during normal driving. The overall impact on the vehicle's weight and efficiency of using a load leveler has yet to be determined, says Williams. Furthermore, developing good control electronics is a challenge, says York.

The hybrid systems that will soon be for sale are all parallel hybrids. One advantage of parallel hybrids is that during steady highway driving, direct mechanical drive avoids the drain of power conversion, says Moore. But parallel hybrids have more mechanical parts than series hybrids. For example, they typically require transmissions, while series hybrids do not.

Toyota plans to unveil a parallel hybrid vehicle in Japan before the year's end. The 1.5-liter engine will be simpler, smaller, and cheaper than a conventional internal combustion engine, says Barnes. It is designed to operate at no more than 4,000 rpms (conventional engines attain more than 6,000 rpms), which allows internal parts to be smaller and lighter, according to Barnes.

Under heavy loads, both power sources will provide torque directly to the wheels. Regenerative braking will conserve energy. Emissions will be markedly reduced compared with a conventional engine, and gasoline-equivalent mileage is projected to be more than 70 mpg. Just how well combustion/electric hybrids will fulfill drivers' needs, at least in the short run, remains uncertain. Says York, "We may need both [series and parallel] types. They may fit the market for different kinds of applications."

Fuel Cells

Another type of hybrid is the fuel-cell powered vehicle. Fuel cells, invented in 1839 by Sir William R. Grove, convert hydrogen chemical energy into electricity. This system can power an electric motor directly or be stored, as in a battery. The mechanism is simple. A catalyst on the anode of the fuel cell splits hydrogen atoms into protons and electrons. Another catalyst on the cathode splits molecular oxygen. The proton travels through a membrane to the cathode, while the electron is conducted through an electric motor (or any other device to which power must be supplied) and ultimately to the cathode. There, the proton, electron, and oxygen combine to form water, which releases energy.

Fuel cells have advanced more rapidly than anyone was anticipating at the time MacCready was conceiving EV1. "Ballard Power Systems met performance standards in 1995 that the U.S. Department of Energy did not expect to be met until five years later," says Williams. The size of fuel cells, which recently were far too big for cars, "has shrunk five-fold in as many years," says Mark. Since the late 1980s, cost of the catalysts has plummeted "80-fold, to the point where [fuel cells] might only cost a few hundred dollars per car," says C.E. Thomas, research director of Directed Technologies, Inc., in Arlington, Virginia. Finally, carbon-fiber wrapped compressed hydrogen tanks, originally developed for aerospace, have recently been adapted for fuel cell cars. "We can put enough hydrogen on board [up to 11,250 pounds per square inch] without using any trunk space to propel the vehicle 380 miles," says Thomas—or more, notes Williams, with lighter and more slippery hypercars.

Ballard and Daimle-Benz announced their joint venture in April. The as-yet unnamed partnership will manufacture fuel cell engines and market them to motor vehicle companies worldwide. At Daimler-Benz, commercial fuel-cell powered cars are officially 5–10 years in the future, says Fred Heiler, manager of public relations for Mercedes-Benz of North America, Inc., located in Montvale, New Jersey. But, he says, "I have a feeling they may be ahead of schedule."

Ford plans to develop a fuel-cell powered P2000 vehicle, and states that "a fully integrated research vehicle could be ready for evaluation by the year 2000." Chrysler Corporation recently announced plans to develop a commercial fuel-cell powered car, which could be in showrooms in 2010, says Christopher Borroni-Bird, an advanced technology specialist at Chrysler. Honda, Volkswagen, Volvo, and Nissan all have fuel cell programs.

One of Ballard–Daimler's chief competitors in the fuel cell propulsion unit business is likely to be Toyota; the company that is probably outspending the United States on alternative automobiles is developing its own fuel cells. "With fuel cells emerging as the most advanced vehicle technology, the debate is shifting from what are the right vehicles to what is the right fuel," says Mark.

Fuel cells can run on pure hydrogen, but hydrogen-carrying fuels such as methanol, ethanol, natural gas, and even gasoline, all of which would be reformed on board, vie for use in fuel-cell powered vehicles. For its buses, Ballard has opted for pure hydrogen. Ford also appears to be focusing on pure hydrogen. Last year, at the international Environmental Vehicles Symposium in Osaka, Japan, Toyota unveiled a pure hydrogen fuel-cell powered version of the RAV4. But Mark thinks the company is turning its attention to methanol. Meanwhile, Daimler-Benz and General Motors are both working with methanol-powered fuel cells.

Chrysler surprised the world of alternative fuels earlier this year when the company announced it would develop gasoline-powered fuel cell cars. The rationale is simple. The biggest obstacles to alternative fuels are the lack of a market infrastructure and the need to "create a massive multibillion dollar distribution network all at once," says Gregory P. Nowell, professor of political science at the State University of New York in Albany. Consumers won't buy cars when fuel is hard to come by, and investors won't finance distribution when customers are few and far between.

But gasoline is a questionable choice for use in a fuel cell. For one thing, the on-board reformer, which extracts hydrogen from the fuel, exacts a stiff penalty in terms of efficiency. For example, a Ford Taurus powered by pure hydrogen would go 66.5 mpg on the energy equivalent of a gallon of gasoline, says Thomas. Powered by gasoline fuel cells, mileage would shrink to 30–40 mpg (although even that's a big improvement over the internal-combustion powered Taurus's overall 21 mpg).

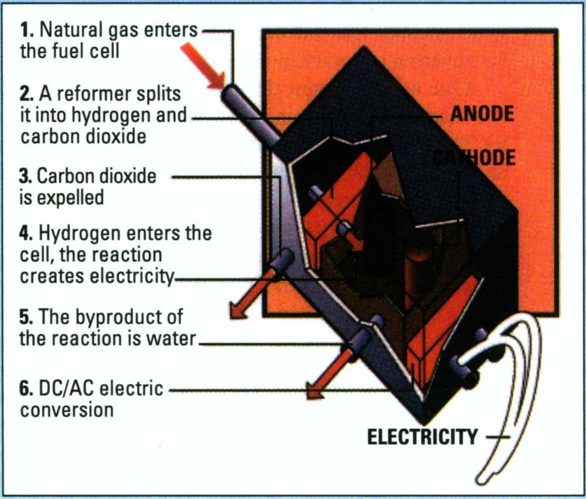
On top of that, "we are probably going to have to have a large battery pack to cope with the transients," says Borroni-Bird, referring to the fact that when the driver hits the gas pedal, the drive system doesn't respond until the reformer has had a few seconds to extract some more hydrogen. Powered by pure hydrogen and unencumbered by a reformer, a fuel cell would respond almost instantaneously, he says, and would require no storage.

Finally, a gasoline-powered fuel cell would still contribute to the greenhouse effect, although smog-

Answering a Propelling Question

The Partnership for a New Generation of Vehicles (PNGV) goals may include developing engines that will be significantly more efficient in using energy. With today's internal combustion engines, after nearly 100 years of refinement, only about 15% of the energy contained in a gallon of gas is actually used to move a vehicle. The rest is heat that is wasted or used to counteract frictional forces or run accessories.

Fuel Cell. A fuel cell is a system in which a fuel reacts with oxygen to produce electricity. When hydrogen is used as the fuel, water vapor is the only emission. Benefits include a potentially diverse fuel supply and zero pollutant emissions. Technical hurdles include cost, size, and weight of fuel cells, as well as storage and production of hydrogen on-board.



Gas Turbines. A gas turbine is an internal combustion engine that functions at a nearly constant and high operating rate of rpm. It is most efficient under a constant load and, for that reason, is used in airplanes and helicopters, and is less suited for stop-and-go driving.

Hybrid Electric Vehicles (HEVs). HEVs are electric vehicles that use more than one power source. They combine the efficiency of a constant operating system, like the gas turbine or the fuel cell, with the acceleration features of an electric motor.

Electric Motor. This is a driving force for the hybrid system.

Advanced Catalysts. Catalysts are materials used to accelerate a chemical reaction, but that are not used up on that reaction. Advanced catalysts would allow for engines to be developed that would run on more oxygen and less gas ("lean burn") than today's engines. Advanced catalysts today rely on costly materials that can withstand high temperatures. The exhaust heat would start the catalytic reaction without fuel.

Direct Injection Diesel Engine. Direct injection diesel engines are among the leading candidate technologies being studied by European and Japanese auto makers for increasing fuel efficiency.

Source: USCAR

producing emissions would be almost nil. "It's almost paradoxical," Borroni-Bird explains, in justifying his company's choice, "but one has to factor in not just the consequences of use, but the probability of usage."

Methanol is easier to reform than gasoline, and a methanol fuel-cell powered Taurus would get the equivalent of 42–49 mpg. As a liquid at ambient temperatures, methanol is easier to handle and store than hydrogen. But Williams sees methanol as a compromise he doesn't particularly want to make. "Mercedes's $350 million makes me think about methanol a lot more than I want to," he says, referring to the Ballard–Daimler joint initiative.

Pure hydrogen provides the greatest efficiency because no energy need be used for on-board reformation of a carrier fuel. Hydrogen-powered fuel cells also produce no pollutants. However, the manufacture of hydrogen using, for example, coal-generated electricity or methanol derived from coal, produces pollutants. But pollutants from fuel cell operation are negligible no matter what the fuel, says Thomas. Some observers see hydrogen as too explosive to use in a car. But Thomas points out that, in the event of a leak, the gas is light enough to dissipate immediately, making it safer than gasoline. And the integrity of the carbon-fiber wrapped hydrogen tanks has been tested by dropping cars from heights that allow them to hit the ground at 52 mph, says Thomas. The tanks have emerged unscathed.

New Fuels, Resources, and Pollution

In conventional engines in conventional cars, methanol and ethanol are hardly less polluting than gasoline. Natural gas is considerably cleaner, and a Ford Crown Victoria running on natural gas can meet California's ULEV standard, says Kreucher. In a hypercar, emissions could drop 10-fold below 1997 cars even with a conventional internal combustion engine and drivetrain, says Williams. Honda has reached the 10% ZEV requirement with its nonhybrid natural gas vehicle, according to Marks. Advanced gasoline or CIDI engines could result in 100-fold reductions in some emissions. The California standards address hydrocarbons, CO, and NOx, but not CO_2. Ford's methanol car only meets the lesser "transitional low-emission vehicle standards." Ford's 80-mpg combustion/electric hybrid P2000, which would use a CIDI engine that Ford is developing, is designed to meet the ULEV standard running on diesel or methanol, says Kreucher.

Hydrogen fuel cell cars would meet California's ZEV standard, while methanol- and gasoline-powered fuel cell cars could meet an equivalent ZEV (EZEV) standard, says Thomas. The EZEV is a standard that some outside organizations, including RMI, are pushing the CARB to implement. Currently, the EZEV is on hold, according to a CARB spokesman. It has been defined, alternatively, as the level of power source emissions generated by use of an EV, and one-tenth of the ULEV standard. EZEV does not dictate the technology used and the source of the pollution—for instance, if you had a tailpipe but it emitted no more pollution than an EV would, it would count as an EV.

Energy Content of Alternative Fuels

Fuel	Btu/Gallon	Ratio of Energy Content Compared to Gasoline[a]
Diesel	129,000	0.89 to 1
Gasoline	115,400	1.00 to 1
E85	105,545	1.09 to 1
Propane	84,000	1.40 to 1
Ethanol, 100%	75,000	1.54 to 1
LNG	73,500	1.57 to 1
M85	65,350	1.77 to 1
Methanol, 100%	56,500	2.04 to 1
Liquid Hydrogen	34,000	3.39 to 1
CNG	29,000	3.98 to 1
Hydrogen	9,667	11.94 to 1

Abbreviations: Btu, British thermal unit; CNG, compressed natural gas; E85, a compound that is 85% ethanol and 15% unleaded gasoline; LNG, liquefied natural gas; M85, a compound that is 85% methanol and 15% unleaded gasoline; psi, pounds per square inch.
[a]These ratios are for energy content in Btus only and do not reflect actual "in-use substitution ratios," which may be more likely due to engine efficiencies.
Source: California Energy Commission World Wide Web site at (http://www.energy.ca.gov/).

As for CO_2, emissions from fossil fuels are proportional to fuel use, so PNGV cars or hypercars would have a huge advantage over today's cars, even if powered by conventional engines and fuels. Net CO_2 from methanol depends on whether the methanol is derived from coal or natural gas, or from biomass, in which case net CO_2 emissions would be close to zero (though there could still be CO_2 emissions from fossil fuels used in farming).

Natural gas would reduce CO_2 emissions to 542 g/mi from 594 g/mi in a gasoline-powered Ford Taurus. In contrast, a gasoline-engine powered fuel cell vehicle would emit 265–381 g/mi, due mainly to the improvement in efficiency, says Thomas. A natural-gas powered fuel cell Taurus would emit 242 g/mi. These figures include refinery emissions. As for resource use, a national fleet composed entirely of PNGV cars would reduce automotive petroleum consumption by nearly two-thirds, all but eliminating oil imports.

At this level of consumption, the United States could produce enough biomass on 3% of the contiguous states to fuel the nation's cars, says Joan Ogden, a research scientist at the Princeton University Center for Energy and Environmental Studies, assuming production of 15 dry tons per hectare per year. That, she says, is based on crops such as switch grass and certain trees that require energy inputs equivalent to only 10% of the energy value of the crop. Alternatively, photovoltaic cells covering .1% of the United States could supply electricity to electrolyze enough water to run the national fleet on hydrogen, says Ogden.

The most intractable obstacle to developing alternative fuels and vehicles is probably that of financing a new market infrastructure, because it is the one problem that may require a political rather than a technological solution.

But the irony of technologies such as fuel cells and hypercars is that each one offers such great potential for energy efficiency and reduced emissions that in the short run, development of any one of them could mitigate pressure for development of the others (although a guiding principle of the PNGV program is that no single technology will be adequate to meet the goal of providing 80 mpg sustainably and affordably). That can be viewed as either a problem or insurance that within the next decade or two, automobiles will become far cleaner and more fuel-efficient than they are today.

David Holzman